Marine Mammals Monitoring for Northwest Fisheries: 2005 Field Year

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Technical Memorandum

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Summary

A field program to monitor marine mammals during winter months in the coastal waters of Washington State has been established using Passive Aquatic Listeners (PALs). Upgrades to existing instruments and new operating software were utilized during the field year 2005. Two offshore moorings at Cape Flattery and one mooring in Haro Strait, deployed synergistically with a visual observation program, were successful. Data demonstrate quantitative acoustic classification of the marine environment. The new software feature, recorded sound bites, assists in the interpretation of the sound field. Specific sound bites containing whale vocalizations were collected and then identified by outside experts. Transient killer whale and Southern Resident (SR) killer whale vocalizations were detected at Cape Flattery. Co-detection of SR killer whales with the visual observation program (D. Bain) confirm the potential for reliable detection of sound-producing marine mammals, in particular, SR killer whales, using passive acoustic monitoring with PALs.

Summary by Task

Task #1: Three available Passive Aquatic Listeners (PALs) were physically upgraded, including new housings to extend the lifetime of the instruments. PALs were deployed on three moorings as directed by the sponsor (NOAA Northwest Fisheries Science Center).

Task #2: New operating software was installed on each PAL. This allowed limited time series "sound bites" to be collected in addition to the traditional PAL data format. These sound bites proved useful for identification of ocean sounds and many contained the vocalizations of the target whale species, namely killer whales.

Task #3: This money was redirected by the sponsor to carry out the field deployment of three moorings. Two moorings were placed offshore from Cape Flattery and one mooring was placed in Haro Strait. The Cape Flattery moorings successfully collected four months of data (April – July 2005). The Haro Strait mooring successfully collected three months of data (May – August 2005), although it had to be redeployed when the mooring release failed prematurely.

Task #4: The PAL data were analyzed to report the ambient noise environment that is present at Cape Flattery. Individual sound bites identify a variety of sound sources. These include wind waves, drizzle, rainfall, local ships,

distant shipping noise, sonars, and whale vocalizations. An ambient sound budget for Cape Flattery is presented. The sound bites containing whale vocalizations were provided to outside experts and identified as transient killer whales SR killer whales (J-Pod), and Pacific white-sided dolphins. PAL data from Haro Strait demonstrate co-detection of SR killer whales with simultaneous visual observations. This demonstrates the potential of passive acoustic instruments, in particular PALs, to effectively monitor for marine mammals, the overall goal of the project.

1. Introduction

Monitoring marine mammal populations is an important component of regulatory and conservation efforts by government agencies. For whales, traditional methods using visual sightings of the animals do not provide continuous or cost-effective results. One animal group of particular interest is the killer whale (orca) pods (Pods J, K, and L) of Puget Sound. Collectively these three groups of animals are known as Southern Residents (SR). The health and status of these animals is of particular interest as they are often in the public view. During the wintertime, these animals leave Puget Sound for the open Pacific Ocean. Their activities and whereabouts during this time of the year are unknown.

Fig. 1. Locations of visual sightings of SR killer whales during the past 25 years.

Making visual sightings of marine mammals at sea is very challenging. Even under ideal weather conditions (calm, good visibility), sightings are limited to a couple of kilometers, and under most conditions (waves, wind, fog, low light) the range for visual detection is even less. During nighttime and in stormy weather, visual sightings are not effective. Figure 1 shows the confirmed

sightings of the SR killer whale pods during the past 25 years. There is less than one sighting per year. However, marine mammals, and in particular whales, communicate underwater with sound. Thus, there are acoustic signals that can be used to detect the presence of the animals. Passive Aquatic Listeners (PALs) have been developed to monitor the underwater sound environment (*Ma and Nystuen*, 2005). In this report, successful field deployments of three moorings using PALs demonstrate the utility of PALs to monitor marine mammals in the ocean.

2. Field Program Description

The 2005 field program consisted of several moorings deployed at locations chosen by the sponsor, NOAA NW Fisheries Science Center (Fig. 2). Table 1 lists the positions of the moorings. The two moorings at Cape Flattery and the mooring in Haro Strait consisted of a single PAL. The typical mooring configuration is shown in Fig. 3. A fourth PAL was deployed on a mooring installed by the Scripps Institution of Oceanography at Westport, WA. The SIO mooring included a HARP (High frequency Acoustic Recording Package) instrument. Unfortunately data from the SIO mooring are not available because of technical problems. The mooring in Haro Strait was placed co-incident with a visual observation program for SR killer whales in Puget Sound (D. Bain).

Table 1. Locations for PAL moorings in 2005

Location	PAL ID	Lat.	Long.	Depth	PAL Depth	Deployment Dates
Cape Flattery	Puffin	48°20.009'N	125°6.897'W	114 m	45 m	4/7/05–7/1/05
Cape Flattery	Ibis	48°20.027'N	125°49.583'W	53 m	43 m	4/8/05–7/1/05
Haro Strait	Osprey	48°30.389'N	123°8.694'W	29 m	21 m	5/13/05–6/9/05 7/8/05 – 9/8/05
Westport (SIO)	Dunlin	46°	125°	66 m	~ 50 m	N/A

Fig. 2. Locations of moorings in 2005

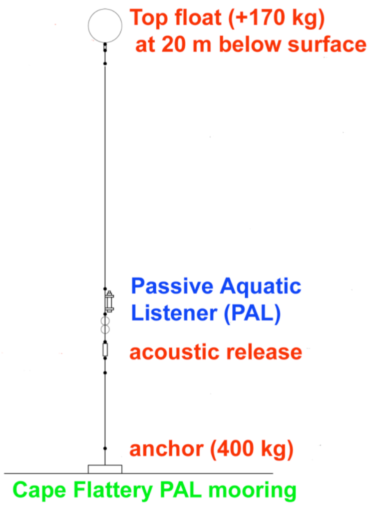


Fig. 3. Typical mooring configuration consists of a float, a PAL, an acoustic release, and an anchor.

3. Passive Aquatic Listeners (PALs)

Physically a PAL is a cylindrical instrument 30 inches long by 6 inches in diameter (Fig. 4). The hydrophone extends from one end. It is typically mounted in a cage to avoid damage by possible fishing lines. The weight in water is about 10 lbs, making it deployable on almost any type of mooring line.

PALs are autonomous and depend on internal batteries for operation. The temporal sampling strategy is designed to allow the instrument to record data for up to one year (*Nystuen*, 1998). To achieve this, the PAL is designed to enter a low power "sleep" mode between each data sample. The principal power usage is from the microprocessor when it is "awake," drawing 43 ma. The microprocessor needs to be in this mode for roughly 30 s for each sample. The microprocessor only draws 0.3 ma when "asleep." The hydrophone, pre-amp, and signal processing board draw 12 ma when "on" and 1 ma when "off." These only need to be "on" for about 2 s per sample, and so the power cost of each sample is 3.8 x 10^{-4} amp-hours. This power demand is met by using three stacks of 10 alkaline D-cell batteries, each with 1.6 AH of energy, a total of 48 AH. Data storage capacity is met using 2 GB flash memory cards.

Fig. 4. A PAL in deployment cage. PALs are robust, passive, relatively inexpensive, autonomous, and smart.

Electronically, PALs consist of a low-noise wideband hydrophone (an ITC-8263), signal pre-amplifiers, and a recording computer (Tattletale-8). The nominal sensitivity of these instruments is –160 dB relative to 1 V/μPa and the equivalent oceanic background noise level of the pre-amplifier system is about 28

dB relative to 1 $\mu Pa^2 Hz^{-1}$. Band-pass filters are present to reduce saturation from low frequency sound (high pass at 300 Hz) and aliasing from above 50 kHz (low pass at 40 kHz). The hydrophone sensitivity also rolls off above its resonance frequency, about 40 kHz. A data collection sequence consists of a 4.5-s time series collected at 100 kHz. This time series is then subsampled four times, generating four 1024-pt or 10.24-ms short time series. The spacing was at 0.1, 1.5, 3.0 and 4.4 s. Each of these subsamples is fast Fourier transformed (FFT) to obtain a 512-point (0–50 kHz) power spectrum. These spectra are spectrally compressed to 64 frequency bins, with frequency resolution of 200 Hz from 100–3000 Hz and 1 kHz from 3–50 kHz. These spectra are evaluated individually to determine the acoustic source and then are recorded internally. Thus, the standard data set is a time series of spectra. The time interval between data collection sequences is variable depending on the acoustic source detected and the mission requirements. For the Cape Flattery moorings, the "sleep time" between samples was set to 5 min and changed to 1 min if a loud noise was detected. For Haro Strait, the sleep time was set to a constant 2 min. These sampling intervals were chosen to be frequent enough so that if a pod of whales remained in the vicinity of the PAL for tens of minutes, a detection was likely to occur.

A modification to the operating software was developed for this project. The intent was to provide validation for the interpretation of the sound spectra time series, and in particular, to save data collection samples that were thought to contain killer whale calls. Typically the original 4.5-s time series for each data collection sequence is discarded. However, these data can be used to provide an audio confirmation of the sound source identification. Practically, these "sound bite" files are relatively large, about 1 MB each, and therefore only a limited number of sound bites can be stored on a PAL. The memory card for a PAL has 2 GB of storage space and therefore about 2200 sound bites can be stored during a given deployment. A "rationing" algorithm was developed to insure that the sound bites were recorded uniformly over the duration of the deployment.

The decision algorithm for storing a specific sound bite was designed for killer whale calls, as killer whale detection was the principal focus of this project. The objective was to collect a maximum number of killer whale calls and then to evaluate those calls for specific killer whale populations, in particular, the unique calls of the SR killer whale populations. A typical killer whale vocalization lasts less than 4 s. Consequently, if the four subsamples report the same spectra, then the sound source present is assumed to be quasi-stationary: wind, rain, drizzle, continuous ship noise, etc., and not a killer whale. Alternatively, if one or more of the spectra are different from one another, then a "transient" sound is assumed to be detected. This sound might be a whale detection. However, transient

sounds associated with shipping, or other biological sources may also meet the transient sound detection criteria. Fortunately, we know the general character of killer whale vocalizations: communication whistles between 1–10 kHz and echo location clicks centered at 20 kHz. If the detected spectrum is consistent with the killer whale signal, the PAL records the entire 4.5-s time series for later analysis. An example of a 4.5-s time series showing a killer whale detection is shown in Fig. 5.

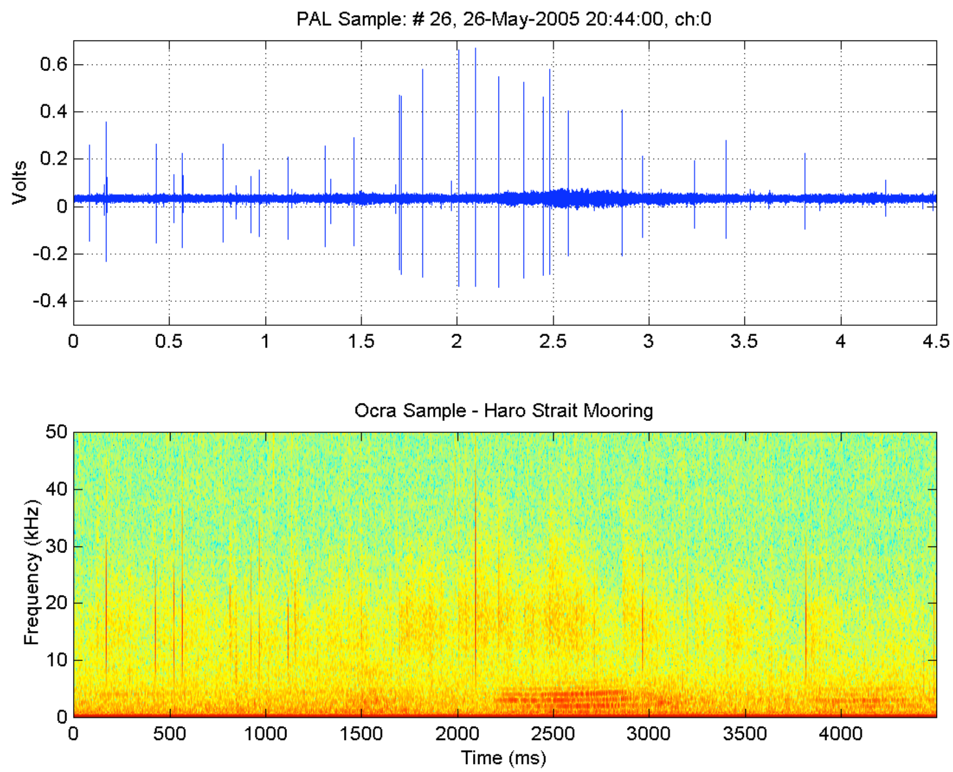


Fig. 5. A 4.5-s time series collected in Haro Strait, 26 May 2005, containing acoustic signals from killer whales. The upper panel shows the time series. The lower panel shows the spectral decomposition of the time series. Several 20-kHz echo location clicks are present and the distinctive tonal whistle between 2 and 5 kHz (at time 2.2 s) identify this sound source as "killer whale." There is visual confirmation that killer whales were present during this recording.

Once a sound bite is thought to contain a killer whale call, the sound bites can be provided to whale experts who have learned to identify specific call types often associated with specific whale pods. In particular, the SR killer whales of Puget Sound have been monitored extensively over many years. Specific call

types have been associated with specific pods (*Foote* 2005; *Foote et al*. 2006), and other calls are associated with Northern Resident killer whales and transient killer whales (*Ford* 1991; 2004). Fig. 6 shows an example of a sound bite containing a killer whale call that was identified as a transient killer whale by several expert researchers.

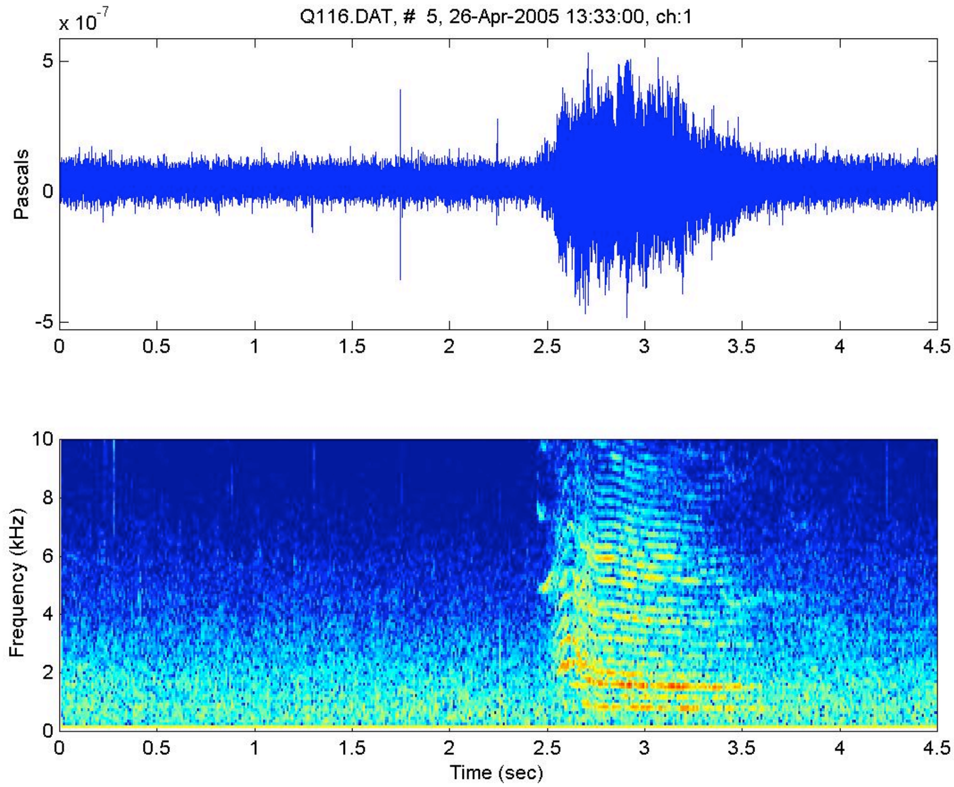


Fig. 6. A 4.5-s time series collected offshore at Cape Flattery, 26 April 2005. The upper panel shows the time series, a single loud call. When presented to experienced whale researchers, this call was identified as a transient killer whale. This type of killer whale is generally silent, and yet comprised most of the calls recorded at this mooring.

4. PAL Data Collected

a. Spectral Time Series

The PAL is not a continuous acoustic sampler. The basic PAL data are a time series of spectral levels between 200 Hz and 50 kHz. The interval between samples is variable depending on that chosen by the user and the intent of the deployment. For the Cape Flattery moorings this interval was 5 min when no unusual sound was detected and 1 min when loud noises were present, e.g., ship, rain, drizzle, etc. Fig. 7 shows a week of PAL data from Cape Flattery in April 2005. The time series of spectral levels typically show slowly changing variations on the time scale of wind associated with breaking wind waves. And indeed, this is a signal that can be used to quantify wind speed acoustically (*Vagle et al*. 1990). But the time records also show short time scale events. These are usually associated with rain, ships, and biological sources, such as whale vocalizations. By examining the spectral characteristics of the sound, one can identify the source and produce a sound budget for a location, including when a source is detected, the percentage of time that a particular source is present, and the loudness of that source (*Nystuen and Howe* 2005).

For the Cape Flattery moorings, several distinctive sound sources have been identified from their generic spectra. These conditions include wind only, drizzle, rain, ships passing close to the mooring, and distant shipping. Mean spectra for each of these sound sources are shown in Fig. 8. This shows that below 2 kHz, the sound of individual ships is much louder than the other sound sources. However, above 20 kHz, the sound of drizzle and rainfall is the louder sound. Distant shipping is a category that is associated with relatively calm seas and apparently good propagation conditions for low frequency sounds. The sound sources are objectively identified by comparing spectral levels, spectral slopes, and persistence of the signal (Fig. 9). The sound bite files are used to verify the acoustic classification.

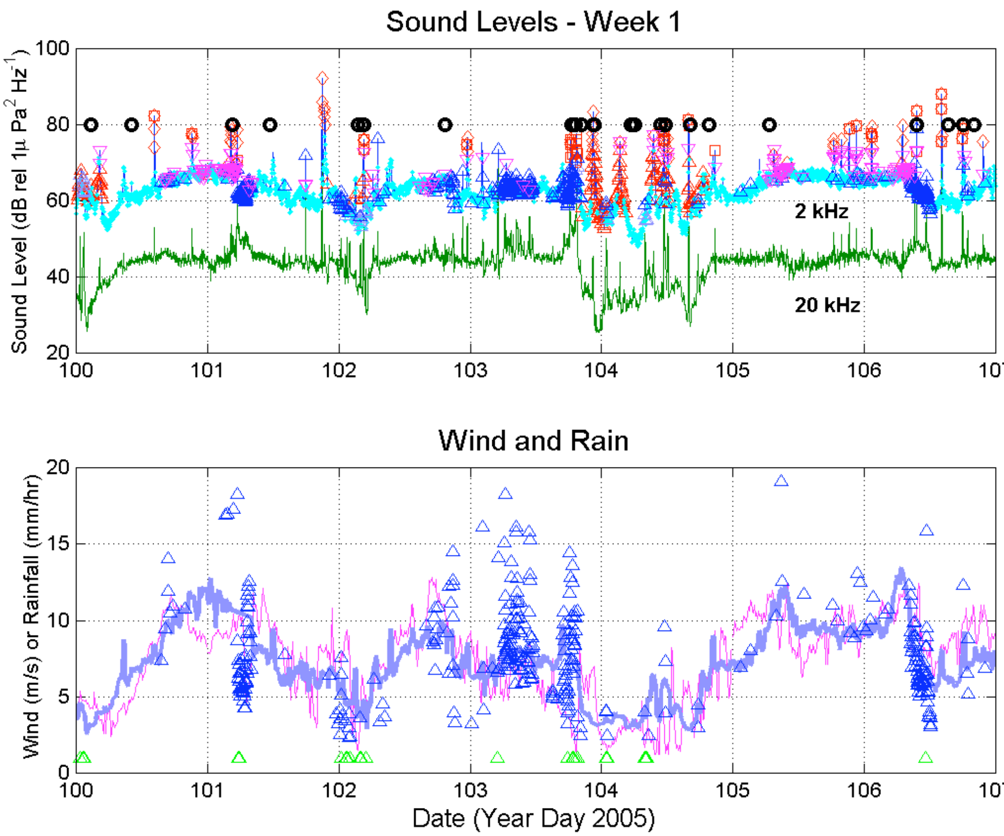


Fig. 7. Week-long time series of underwater sound levels from Cape Flattery in April 2005. The sound sources have been identified by their spectral character and are superimposed on the 2-kHz sound level curve. Ships are shown in red; rainfall in blue. Sound bites are shown in black and are used to verify the acoustic classification of the sample. The lower panel shows the geophysical interpretation of the sound record. The blue curve is the acoustic wind measurement (*Vagle et al. *1990). It is compared to the wind speed record from the NOAA weather buoy #46087. Acoustic rainfall measurements are shown in blue (triangles) (*Nystuen *2001;* Ma and Nystuen *2005).

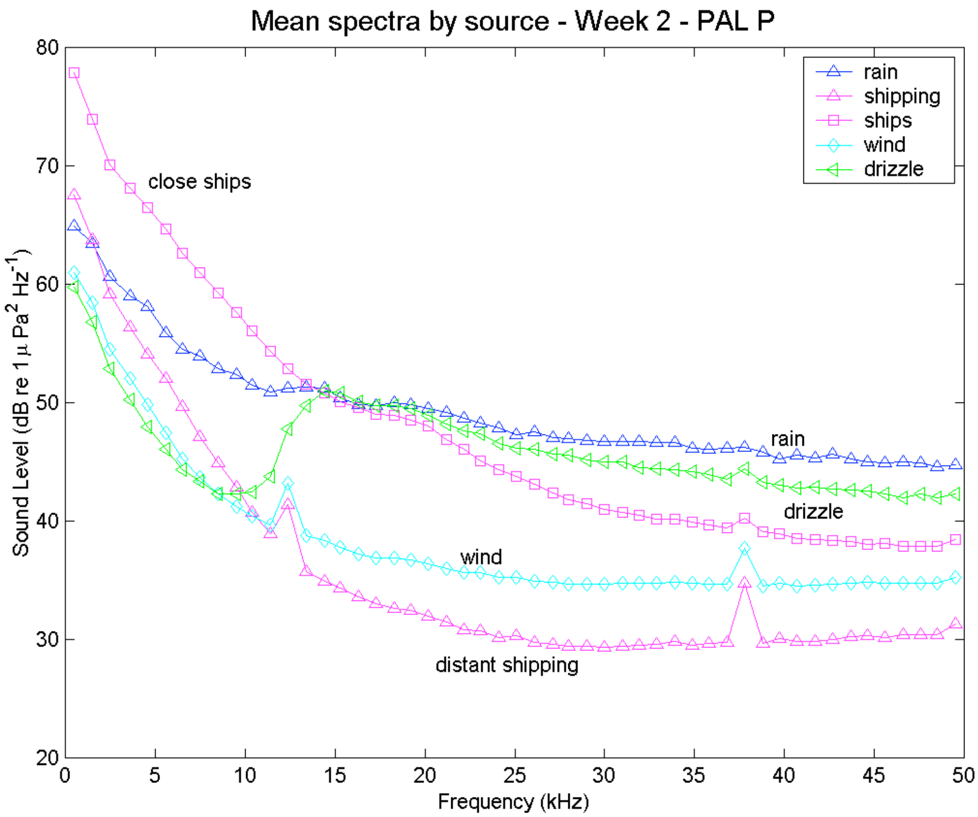


Fig. 8. Mean sound spectra for different sound sources during Week 2, Cape Flattery PAL mooring, April 2005. Rain and drizzle are the dominant sound sources above 20 kHz. Close ships dominate the sound field below 10 kHz.

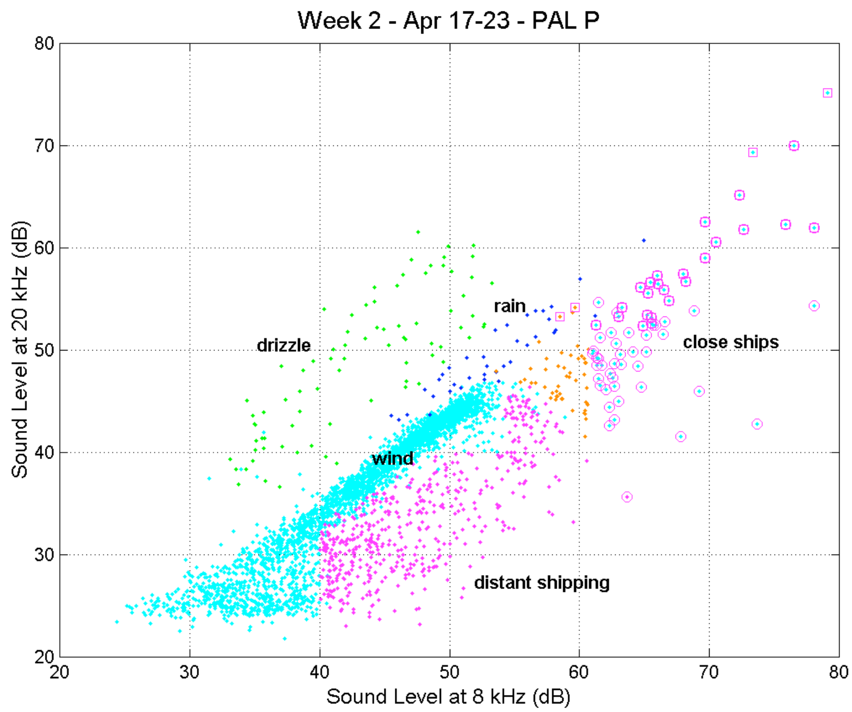


Fig. 9. Scatter diagram comparing the sound level at 8 kHz versus 20 kHz for individual data samples during Week 2 of the Cape Flattery deployment (PAL Puffin). Different sound sources (drizzle, rain, close ships, distant shipping, and wind) occupy distinctive positions on these types of scatter plots.

b. Sound Bites

The new feature of the PAL data is the 4.5-s time series that is recorded depending on pre-programmed criteria. Each deployment has hard disk space for about 2200 of these recordings. They are used to verify the sound source present, allowing correct interpretation of the stored spectra from the PAL. They can also be monitored audibly for whale calls. These potential call records are then selected for further analysis. To insure that the computer did not fill the memory card with too many files from a single day and to allow every day of the deployment a potential to save some sound bites, a quota for number of saves per day was imposed. This quota is set as a function of anticipated deployment length and an upper limit of about 2200 saves for the entire deployment.

Four PALs were deployed during the 2005 field season (Table 1). One was co-located with a HARP deployment at Westport, WA. This PAL was not running the new software, and furthermore, it suffered an electrical connection

failure between the computer and the circuit board. No data are available. The other three deployments were successful, including recording of sound bites and detection of whales.

PAL Puffin was deployed at 48° 20.009′N 125° 6.897′W in 114.3 m of water at a depth of 44.8 m. The mooring was in the water from 8 April to 1 July 2005. A total of 988 sound bites were recorded over 85 days. Suspected killer whale calls were recorded on 11 days. These files are summarized in Table 2.

PAL Ibis was deployed at 48° 20.009′N 124° 49.583′W in 53.2 m of water at a depth of 43.7 m. This mooring was also in the water from 8 April to 1 July 2005. The sampling quota was reached during each day of the deployment. A total of 1680 sound bites were recorded. Only 7 sound bites, on 4 days, are suspected killer whale calls. Most of the sound bites recorded "tapping" and there is a strong tidal pattern to the sound, suggesting noise associated with local currents. Nevertheless several suspected killer whale sound bite files were recorded and are summarized in Table 3.

PAL Osprey was initially deployed in Haro Strait on 15 May 2005 at 48° 30.389′N 123° 8.694′W in 29.2 m of water. This location is very near to the shore of San Juan Island. It is in the "north" observation area for David Bain's killer whale observation project, and the deployment was designed to coincide with his project. The acoustic release failed prematurely on this mooring. The mooring surfaced on about 9 June 2005 and was on the surface for a couple of weeks. It was observed, but not reported to APL-UW. Finally the tag line to the anchor separated and the mooring drifted north and was recovered by Ken Balcomb while on its way to Canada. Finally APL-UW was notified and the mooring was returned. It was redeployed on 8 July 2005 at 48° 30.416′N 123° 8.729′W in 28.8 m of water and recovered on 4 September 2005. David Bain's project ended on 31 July 2005. The deployment quota for sound bites included a restriction on the time of day, to coincide with the 6 am – 2 pm visual observation schedule, and with a temporal spacing of "every 20 min" to sample the background regardless of triggering. An average of about 30 sound bites per day were recorded during the first deployment. The daily quota was higher during the second deployment and about 35 sound bites were recorded each day, with a maximum of 66 on 22 July 2005. Roughly 40 sound bites have suspected killer whale vocalizations. The suspect killer whale sound bites for the Haro Strait PAL deployment are in Table 4.

Table 2. Summary of sound bites containing suspected whale calls at the offshore Cape Flattery mooring (PAL Puffin). File ID gives the PAL ID (Q for Puffin), the date, and the sound bite number for that date.

File ID	Date	Time(GMT)	Comments
Q108_3	4/18	08:08	drizzle with weak call
Q108_4	4/18	09:11	drizzle and 2 calls
Q115_5	4/25	02:13	two calls – maybe
Q116_5	4/26	13:33	transient whale call – very loud
Q116_8	4/26	18:00	brief calls, some clicks
Q116_11	4/26	22:24	loud clear calls
Q116_12	4/26	22:26	clear calls
Q120_4	4/30	09:12	clicks and calls
Q120_5	4/30	09:47	weak calls
Q120_6	4/30	10:43	probable call
Q123_3	5/3	05:12	weak call
Q123_5	5/3	07:22	two calls
Q148_3	5/28	03:38	loud clear calls
Q148_6	5/28	04:23	buzz @ 15 kHz
Q157_3	6/6	01:08	low freq call
Q157_4	6/6	02:52	groans and high freq clicks
Q157_5	6/6	03:12	groans and high freq clicks

Days 177–180 (26–29 June) had long records of nearly continuous whale call detections. The character of the calls is “squeaky” with long periods of high frequency “clouds” from 30 to 50 kHz. Each day the quota for number of sound bites (30) was reached. These sounds have subsequently been identified as Pacific white-sided dolphin whistles and clicks.

(Day 177 = 6/26/05)

Q177_5	03:30	squeak
Q177_6	03:50	broadband cloud (30-50 kHz) and one weak call
Q177_8	03:54	bb cloud and weak call
Q177_10	06:55	bb cloud and weak call
Q177_13	07:31	squeaks?
Q177_14	08:00	squeaks and bb clouds

Table 2, continued

(Day 178 = 6/27/05)		
Q178_2	04:52	quick call, broadband noise cloud
Q178_5	05:30	squeaky call, bb cloud
Q178_6	05:35	multiple short calls
Q178_12	07:54	call and bb cloud
Q178_13	08:14	faint calls and bb clicks
Q178_14	08:24	ditto
Q178_15 to 22	08:28 to 09:08	calls and bb clouds
Q178_23	09:49	loud call (cutoff) and bb cloud
Q178_24	09:57	very loud click packets
(Day 179 = 6/28/05)		
Q179_13	05:25	squeaky calls
Q179_14	06:01	5 high freq buzz packets
Q179_15	06:20	3 calls and broadband noise clouds
Q179_16	06:32	squeaky calls and clouds
Q179_17 to 26	06:59 to 08:15	squeaky calls and bb clouds
Q179_27	08:17	squeaky calls, but mostly clouds
Q179_28	08:27	ditto
Q179_29	08:51	just high freq cloud
Q179_30	09:01	faint squeaks, clouds and clicks
quota for day reached		
(Day 180 = 6/29/05)		
Q180_1	01:25	groans, clicks and calls
Q180_2	01:27	call, some clicks
Q180_3	02:25	squeaky calls, groans
Q180_4	02:30	squeaky calls, groans
Q180_5	02:47	squeaky calls, some bb cloud
Q180_6	02:59	squeaky calls, tapping
Q180_7	03:10	calls and tapping
Q180_8	03:18	calls, taps and clicking
Q180_10	03:52	squeaky call
Q180_14	08:18	3 weak calls, hi freq clouds
Q180_15	08:24	buzz packet, clear calls
Q180_16	08:31	calls
Q180_18	08:52	call and cloud
Q180_19	09:02	quiet call and clouds
Q180_20	09:06	calls and clouds
Q180_22	09:18	calls and clouds
Q180_23	09:20	high freq packets and weak calls
Q180_24	09:30	weak calls and clouds
Q180_25	09:36	squeaky calls and clouds
Q180_26	09:44	squeaky calls
Q180_27	09:54	clouds and weak calls
Q181_13	10:59	squeaky call (clouds earlier in day)

Table 3. Sound bite summary for the inshore Cape Flattey mooring (PAL Ibis). File ID gives the PAL ID (I for Ibis), the date, and the sound bite number for that date.

File ID	Date	GMT	comments
I102_8	4/12	03:59	distant call, with some tapping
I112_8	4/22	03:58	clear call
I114_11	4/24	06:39	squeak – doubtful
I129_9-12	5/9	0505 to 0515	clear calls

Table 4. Suspected whale sound bite file summary for the Haro Strait mooring. Visual confirmation is from the Bain observation program and indicates that whales were in the vicinity of the mooring at the time of the acoustic detection. Local time (LT) is given. File ID gives the PAL ID (O for PAL Osprey), the date, and the sound bite number for that date.

File ID	Date	LT	visual	comments
O137_16	5/17	10:48	yes	broadband clicks, one quiet call
O137_20	5/17	11:54	yes	loud call
O137_21	5/17	11:56	yes	loud call cutoff
O139_7 to 11	5/19	6:38 to 6:56		30-50 kHz clicks
O139_15	5/19	07:30	no	broadband clicks
O139_17	5/19	07:42	no	broadband clicks with taps
O139_18	5/19	7:46	no	high freq calls with tapping
O139_36	5/19	12:54	no	loud call
O139_37	5/19	13:00	no	2 partial calls
O141_19	5/21		yes	call
O144_15	5/24		yes	broadband clicks during visual observations
O146_26	5/26	13:44	no	nice orca call and clicks
O148_12	5/28	09:46	yes	call with boat noise
O150_13	5/30		yes	
O150_14	5/30	10:15	yes	call and clicks
O151_17	5/31		yes	call, broadband clicks follow
O153_34	6/2	10:48	yes	partial call, broadband snaps
O154_30	6/3	13:00	yes	loud call and broadband clicks
O157_06 to 12	6/6	07:30	no	various calls and broadband clicks – K POD
O160_24	6/9	08:12	no	quick calls and bb clicks
O197_13	7/16	08:54	yes	one short call and clicks
O197_14	7/16	08:58	yes	clicks, call and drizzle
O197_15	7/16	09:04	yes	high frequency clicks
O197_17	7/16	09:12	yes	high frequency buzz packet
O197_30	7/16	11:14	yes	1 brief call and sonar ping
O197_31	7/16	11:30	yes	3 calls, clicks
O197_49	7/16	13:12	yes	ship, clicks, taps and one call
O197_54	7/16	13:58	yes	two calls, sonar ping and clicks
O199_23	7/18	10:56	yes	2 calls
O199_24	7/18	11:10	yes	2 calls with broadband clicks

5. Data Analysis and Discussion

a. Sound Budget for Cape Flattery

A sound budget describes the relative time that different sound sources are dominant at a location, and then describes their relative loudness. An example of a sound budget analysis is shown in Figs. 7–9. Over a given period of time, the sound record is objectively sorted to identify several different sound sources. For the Cape Flattery moorings the sound classifications are wind, rain, drizzle, ships passing close, and distant shipping. The two shipping categories are differentiated by loudness and the character of the event. Ships passing close to the mooring have high sound levels at all frequencies and generally take about 30 minutes to pass. Distant shipping is the label given to times when the sound levels at low frequency are elevated, but the sound levels at high frequencies are not. Individual events are less obvious, but overall the character of the sound spectrum is to have relatively more sound at low frequency compared to wind only spectra (Fig. 8). This is because for long range propagation in the ocean the higher frequencies are absorbed more quickly than low frequencies, and consequently the spectra have relatively high values at low frequency. However, if a ship passes close to the mooring, it can produce high sound levels at all frequencies. Drizzle is another very unique and loud sound underwater and is distinguished from rain when the sound levels between 13 and 25 kHz are high relative to lower frequencies (5–10 kHz). These categories of sound sources are identified on scatter diagram such as is shown in Fig. 9.

For each week of the deployment at the offshore mooring at Cape Flattery (48° 20.009′N 125° 6.897′W, PAL Puffin) the sound budget was calculated and a summary given (Table 5). The category “shipping” refers to “distant shipping” as previously described, although it is probably an indication of local fishing boat activity. The “ships” category is the “loud at all frequencies” events that are associated with a ship passing close to the mooring. At this location, shipping noise dominates the underwater sound field about 10–30% of the time. The weeks with low “shipping” were weeks with bad weather, consistent with the expectation that local fisherman were not fishing at those times. And conversely, weeks with low rainfall and presumably good weather, have higher “shipping” activity. Furthermore, as the season progressed from April (Week 1) to July (Week 12), the shipping activity increased. Sound associated with rainfall dominated 1–10% of the time.

Once the sound sources are identified, the relative loudness is calculated. Week 2 of the deployment (Fig. 8) is typical of the other weeks. The relative

loudness of the sources is a function of frequency. Rain and drizzle are usually the loudest noise above 20 kHz, while the loudest sounds below 2 kHz are from ships. The signals from wind and rain can be used to quantify wind speed (*Vagle et al*. 1990) and rainfall rate, respectively (*Nystuen* 2001; *Ma and Nystuen* 2005). This shown in Fig. 7.

The inshore mooring at Cape Flattery (48° 20.009′N 124° 49.583′W) was in shallow water near the shore. The sound record was frequently contaminated with a pulsed clicking, with spectral components between 2 and 10 kHz. This noise source was ubiquitous but loudest during periods of high local currents. This suggests a mechanical noise associated with the mooring, but the exact source of the sound remains a mystery. It could be a biological source. The sound bites were insufficient to establish its identity.

***Table 5. Sound budget calculations for the offshore mooring at Cape Flattery. The percentages of time that each sound source is dominant are given. The category "shipping" refers to "distant shipping" although it is probably an indication of local fishing boat activity*.**

	Wind	*Rain*	*Drizzle*	*Ships*	*Shipping*
4/10–4/16	81.2	9.2	0.9	4.9	3.6
4/17–4/23	80.2	2.7	1.8	4.4	12.7
4/24–4/30	75.8	0.5	3.6	2.9	17.2
5/1–5/7	72.8	0.1	6.7	4.0	15.7
5/8–5/14	67.9	0.6	1.9	12.5	16.9
5/15–5/21	79.8	5.8	3.5	3.1	6.7
5/22–5/28	79.5	1.5	0.3	8.2	11.7
5/29–6/4	72.5	0.8	3.4	10.3	15.3
6/5–6/11	72.9	0.5	0.9	7.6	17.3
6/12–6/18	69.5	1.1	5.6	9.5	19.0
6/26–7/3	59.6	1.7	5.7	6.7	21.4

b. Sound Bite Identification

The sound bites thought to contain whale vocalizations (Tables 2–4) were provided to several researchers specializing in killer whale call identifications (*Ford* 1991 and 2004; *Ford and Foote* 2006; *Foote et al*., 2006). Killer whales have a wide repertory of calls. These calls have been studied and various "call

types" have been identified. Different groups of killer whales consistently use a selection of these call types, suggesting a local dialect that can be used to identify the specific group of killer whales that are present. For example, the call type "S1" is usually associated with the SR J-Pod. The sound bites were considered barely adequate to identify the caller. While entire calls were captured by the 4.5-s sound bites, the experts wanted to have longer sound bites so that multiple calls could be used to verify the classification. Nevertheless, call types were identified, and can be used to state that a specific whale type was probably present. The results for the Cape Flattery moorings are shown in Table 6. Transient killer whales are known to be relatively quiet as their preferred prey (marine mammals such as seals) can hear in the killer whale vocalization frequency range. SR killer whales (Pods J, K, and L) prefer to eat fish (salmon) and are more vocal. It is interesting to note that more detections of transient killer whales than SR killer whales occurred at Cape Flattery. The goal of the project is to detect the SR killer whales in the Pacific Ocean during the winter months. The likely detection of J-Pod killer whales at Cape Flattery on 18 and 25 April, and 3 May is a successful demonstration of passive monitoring for specific marine mammal populations.

The Haro Strait mooring also recorded many whale vocalizations. All of these were identified as SR killer whales. Visual observations (next section) confirmed these identifications, but again the researchers wanted longer sound bites to confirm the exact pod that was present.

Table 6. Summary of whale sound bite identifications at Cape Flattery in 2005. The "Q" sound bites are from the mooring at 48° 20'N, 125° 07'W and the "I" sound bites are from the mooring at 48° 20'N, 124° 50'W. The call types are recognized calls associated with killer whales. These are often pod specific, allowing identification to pod. The S1 is typically given by Southern Resident J-Pod whales. The T3 and T7 calls are given by West Coast transient killer whales. Pacific white-sided dolphins were detected for long time periods on 29–29 June.

Date	Sound Bite #	Call type	Whale type
Apr 18	Q108_3/4	S1	SR J-Pod
Apr 22	I112_8	T7	Transient KW
Apr 25	Q115_5	S1	SR J-Pod
Apr 26	Q116_5	T7	Transient KW
Apr 30	Q120_4,6	T2?	KW, not identified
May 3	Q123_3,5	S1?	SR J-Pod
May 9	I129_9-12	T3, T7	Transient KW
May 28	Q148_3	T3, T7	Transient KW
Jun 6	Q157_3	Low frequency	Baleen whale?
Jun 26–29	Lots	Squeaks and clicks	Pac WS Dolphins

c. Validation of Killer Whale Detection Using PALs in Haro Strait

It is recognized that the duty cycle of a PAL is low. Thus, a co-located program of visual observations of killer whale behavior (Bain) and the PAL mooring in Haro Strait was established to verify the effectiveness of passive acoustic monitoring for orcas. Fig. 10 shows the sound record during the afternoon of 28 May. Visual observations of killer whales occurred over a period of several hours. Many small whale watching boats were also present. The sound bites were recorded at a regular 20-min interval from 6 am (LT) to 2 pm (LT), and several sound bites containing killer whale clicking and calls were triggered. The figure shows total sound level, the integrated sound over the full frequency range of the PAL (200 Hz–50 kHz), along with times when the visual observers were tracking whales near the mooring, and the times when sound bites were recorded.

Clusters of four points together indicate a persistent sound, such as a boat engine, over the duration of the acoustic sample (four spectra per 4.5-s sample are analyzed). The two loud events between 9:00-10:00 LT are examples of this type of clustering. Fig. 11 shows the sound bite at 13:44 LT, when several small whale watching boats were in the vicinity of the mooring. An individual loud point, such as at 7:36 LT or 8:36 LT, is an indication of a brief transient sound, such as an echo location click or a whale call. The sound bite at 7:38 LT (Figs. 12 and 13) contains a series of clicks that show the spectral content of the clicks. And finally, the sound bite at 9:33 LT (Fig. 14) contains several calls and background boat noises. This was just a few minutes before a visual observation track of a killer whale in the vicinity of the mooring commenced.

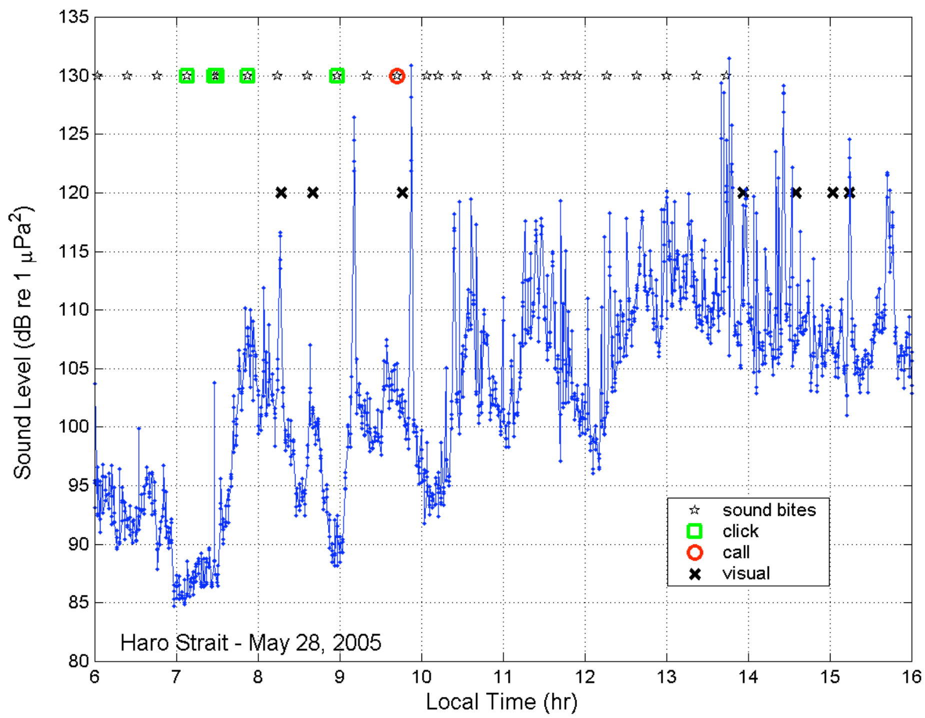


Fig. 10. The sound record during 28 May 2005 at the Haro Strait PAL mooring. The times of sound bites and visual observations are shown with symbols. Five sound bites contained echo location clicking and one contained a call.

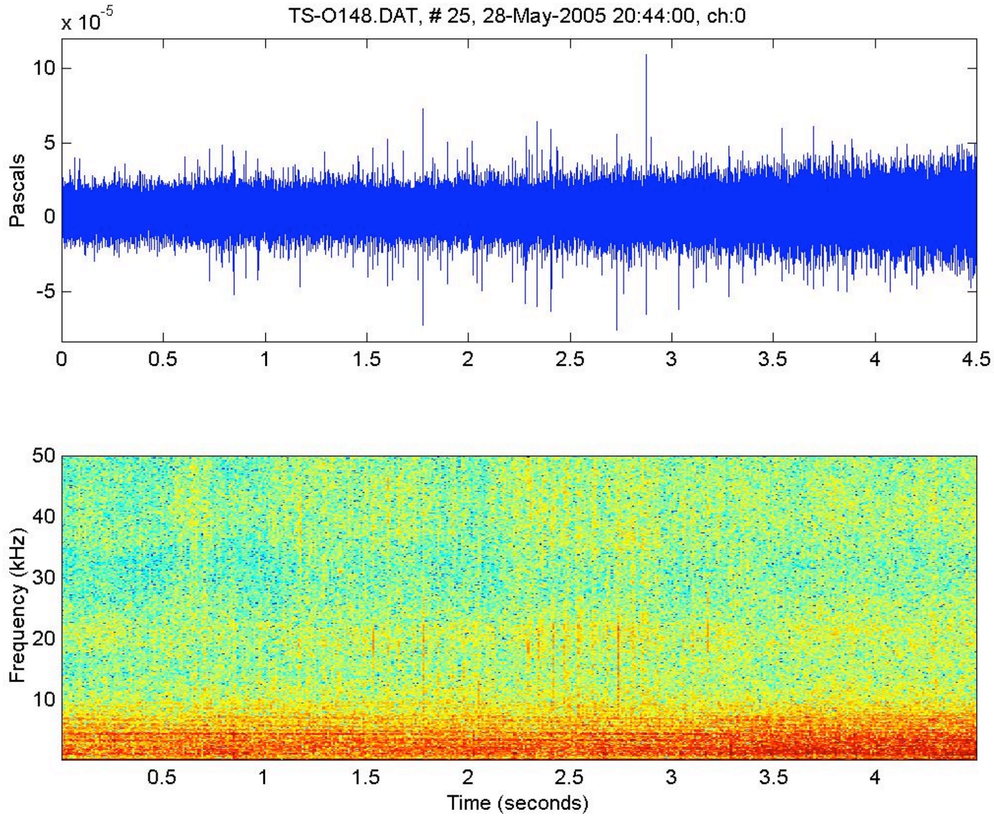


Fig. 11. Sound bite containing the whine of a small boat engine at 20:44 UTC (13:44 LT). This is likely to be a small whale watching vessel. This is Sound Bite #25 of day 148. Several small boats were present near the mooring at this time.

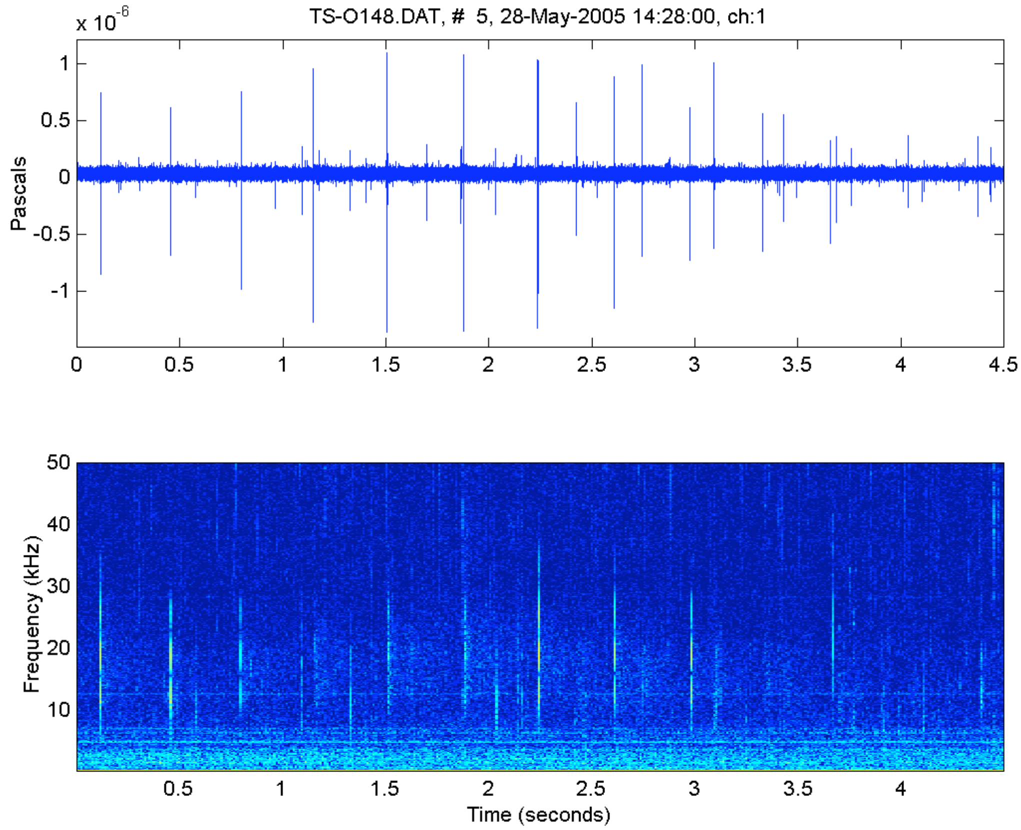
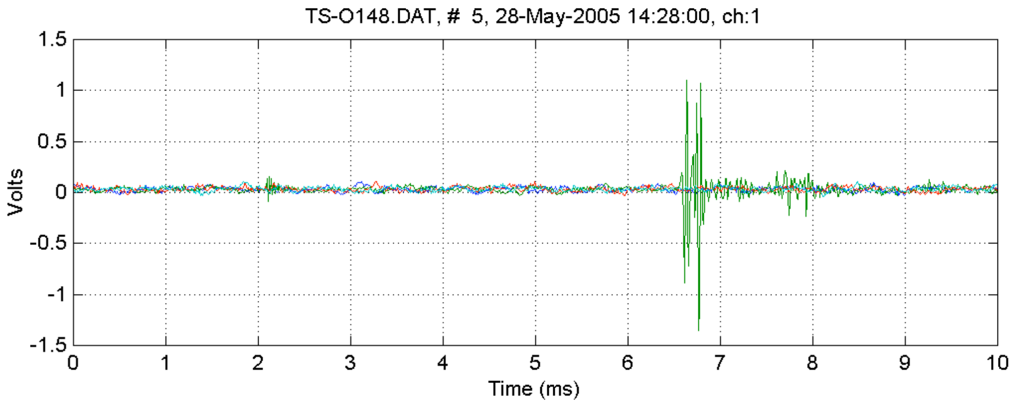


Fig. 12. Sound Bite #5 at 7:28 LT (in Fig. 10) on 28 May showing echo location clicking from killer whales.



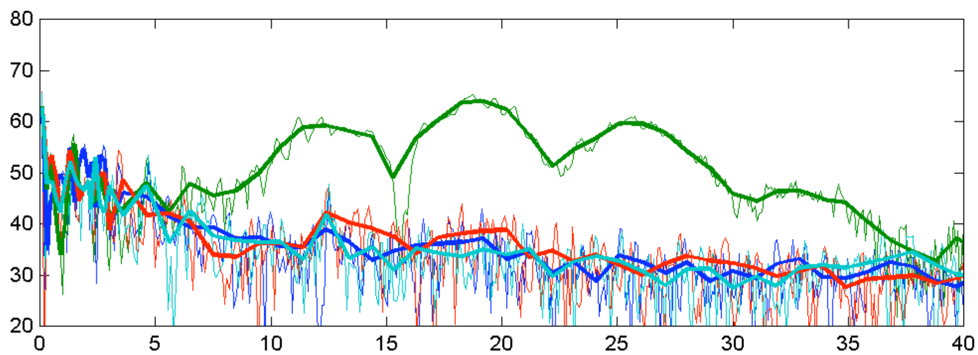


Fig. 13. Analysis of a killer whale echo location click. The top panel shows the subsamples from the sound bite shown in Fig. 12. An individual "click" is recorded. Its spectral character is shown in the bottom panel, showing a broadband signal centered at 20 kHz.

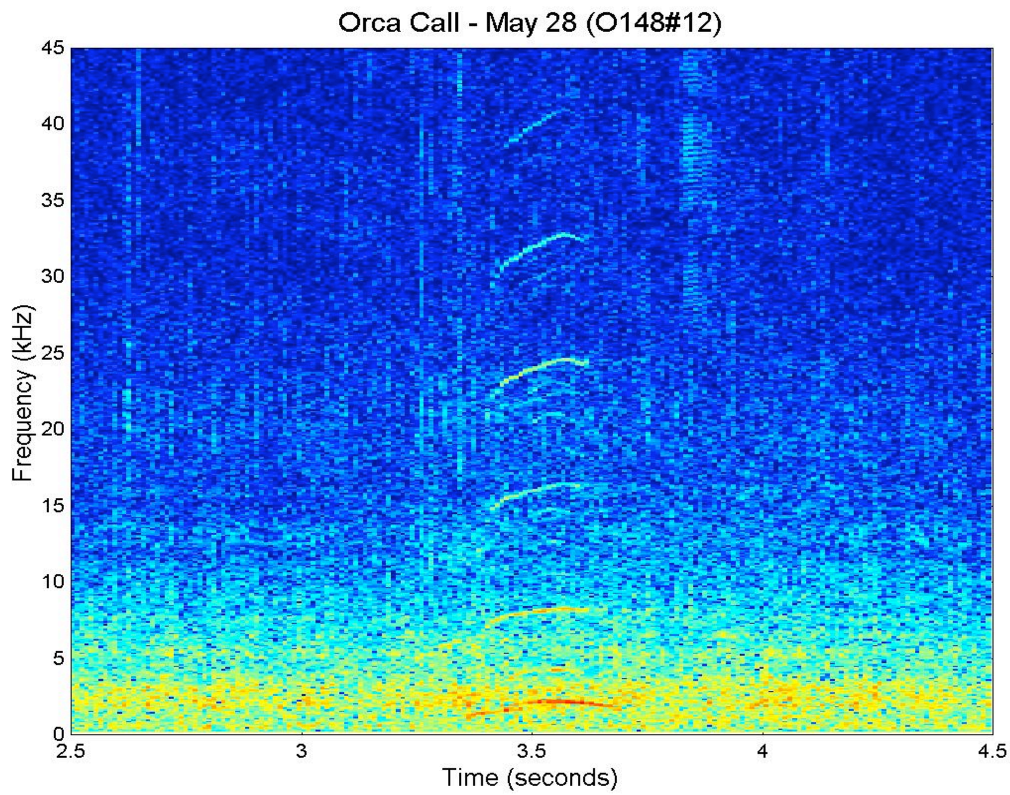


Fig. 14. Sound Bite # 12 from 28 May showing a killer whale call (at time 3.5 s) in a background of local boat noise. Visual observations that whales were present occurred a few minutes after this recording.

Table 7 reports the summary of visual and acoustic co-detections of killer whales in Haro Strait. During the first deployment period (15 May to 9 June 2005) comparison with David Bain's observations show co-detection 7 times of 9 visual observations, and no visual confirmation of acoustic detections on 4 other occasions. However, Bain's group was not working on three of these occasions and reported whales nearby on the fourth day, but not in the visual tracking range for their observation program. Whale watchers reported whales in the vicinity of San Juan Island on another two of these days. This is a reassuring result that a low duty cycle recorder has the capacity to reliably detect vocalizing whales when they are in the listening range of the instrument for a period of time. The probability of detection is a function of how vocal the animals are when they are in the vicinity of a recorder, how long they are in the vicinity of the recorder, and the duty cycle of the recorder. The performance was poorer during the second deployment (8–31 July 2005) when just 2 of 6 visual observations were co-

detected acoustically. Both acoustic detections were confirmed with visual observations.

Table 7. Summary of visual and acoustic co-detections in Haro Strait. *The visual observers were off work on 5/19, 6/6, and 6/9, but whales were observed in the vicinity of the mooring on 5/26, 6/6, and 6/9.

Date	Visual Observers	PAL
5/17	11:05-12:04	10:48-11:56
5/19	Off work	6:38-13:00
5/21	11:20	11:46
5/24	8:38-10:45	8:34-10:26
5/26	No*	13:44
5/27	10:13	No
5/28	8:17-15:14	9:46
5/30	10:33-13:24	10:12-11:26
6/2	10:41	10:48
6/3	10:19-12:49	13:00
6/6	Off work*	7:30-10:00
6/7	8:04-13:39	No
6/9	Off work*	8:12
Mooring out of water		
7/11	8:59-12:42	No
7/16	9:24-13:41	8:54-13:58
7/19	11:55-12:32	10:56-11:10
7/26	11:59-12:46	No
7/27	8:50-11:48	No
7/30	15:44-16:15	No

6. Summary and Conclusions

This project has demonstrated the utility of a low duty cycle acoustic recorder, specifically a Passive Aquatic Listener (PAL), to monitor the marine environment for marine mammals, specifically SR killer whales of Puget Sound, when those animals are away from Puget Sound during the winter months. Two moorings were placed offshore from Cape Flattery, WA from April to July 2005. The PALs were used to quantify the background sound budget for Cape Flattery. Measuring the background sound environment in which marine mammals live is an important component for understanding their ecology. The spectral and temporal characteristics of different sounds are used to identify the sound sources. Weekly sound budgets showed that ship generated noise was a dominant sound source 10–30% of the time. Precipitation generated sound was a dominant sound source 1–10% of the time.

A new feature of the PAL recorder is 4.5-s "sound bites" recorded at 100,000 Hz. These sound bites are used to verify acoustic classification of the sound sources. They verified the presence of ships and also contained transient calls associated with whale vocalizations. The sound bites containing suspected whale vocalizations were compiled and provided to expert whale researchers (Ford, Foote). Call types associated with specific groups of killer whales were tentatively identified. The researchers suggested that 4.5-s time series were barely adequate to make a definitive identification and would have preferred longer sound bites.

A third deployment in Haro Strait was used to investigate the effectiveness of a low duty cycle acoustic recorder to detect killer whales. Visual observations provided validation of killer whale presence. During a four-week period (15 May – 9 June 2005), visual observations of killer whales present were co-detected 7 of 9 times. Four additional acoustic detections occurred when the visual observers were not working, or the whales were seen nearby but not in the tracking range of the visual observation program. This demonstrates the detection potential for low duty cycle recorders, even in a noisy marine environment. It also demonstrates the ability of the acoustic recorder to detect animals at times when visual observations cannot be made.

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13. ABSTRACT *(Maximum 200 words)*

A field program to monitor marine mammals during winter months in the coastal waters of Washington State has been established using Passive Aquatic Listeners (PALs). Upgrades to existing instruments and new operating software were utilized during the field year 2005. Two offshore moorings at Cape Flattery and one mooring in Haro Strait, deployed synergistically with a visual observation program, were successful. Data demonstrate quantitative acoustic classification of the marine environment. The new software feature, recorded sound bites, assist in the interpretation of the sound field. Specific sound bites containing whale vocalizations were collected and then identified by outside experts. Transient killer whale and Southern Resident (SR) killer whale vocalizations were detected at Cape Flattery. Co-detection of SR killer shales and the visual observation program (Bain) confirm the potential for reliable detection of sound-producing marine mammals, in particular, SR killer whales, using passive acoustic monitoring with PALs.

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